TECHNOLOGY STATUS — BATTERIES AND FUEL CELLS

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SUMMARY

The current status of research and development programs on batteries and fuel cells and the technology goals being pursued are discussed. Emphasis is placed upon those technologies relevant to earth orbital electric energy storage applications.

INTRODUCTION

Discussions of orbital energy storage usually have concentrated upon the details of the nickel-cadmium battery system. Even though tried and true, this system has limited capability and we must look to alternatives, especially with the growth in projected power levels and life for orbiting systems. This paper attempts to give a brief overview of the electrical storage technologies that are essential to those missions. The technology, the approaches being taken, and their current status are summarized in the figures, which are copies of the VU-graphs used in the oral presentation. Rechargeable battery technology will be reviewed first, followed by fuel cell technology. Fuel cells form one part of the fuel cell-electrolyzer system, which has promise for very large orbital storage application. The paper which follows this one will discuss these particular systems in more detail.

SECONDARY-BATTERY TECHNOLOGIES

The technology objectives for secondary batteries for orbital applications are long cycle and calendar life, high energy density, efficiency, reliability, and low cost. Advances are achieved through technology programs in cell components (separators, electrodes, etc.), materials (which, common to many energy technologies, are often critical to advancement), thermal management, designs, operating techniques (to provide optimal conditions and reconditioning possibilities) and test-evaluation procedures which permit valid, rapid verification of new concepts. Entirely new systems must be explored and defined to continue the evolutionary process. Kerr and Pickett (ref. 1) recently examined space battery technology for the 1980's. Figure 1 summarizes the current performance of orbital storage batteries against the demanding requirements of typical low earth orbit (LEO) and synchronous (SYNC) orbit applications. The nickel cadmium system is used. Further improvement towards the "ultimate" nickel-cadmium battery is being sought in the joint Jet Propulsion Laboratory-NASA Lewis pro-

gram with the cooperation of Goddard Space Flight Center and the Air Force. This program has been described (ref. 2) and is summarized in figure 2. A prototype cell is to be demonstrated by October 1981. Multikilowatt applications require larger cell sizes in excess of 100 ampere hours (AH) that can be actively cooled. As shown in figure 2, a new toroidal construction is the subject of a current feasibility study. The projected energy density and life for the advanced nickel-cadmium technology in LEO and SYNC in comparison with the state-of-the-art are shown in figure 3.

A higher energy alkaline battery, the long-life rechargeable silver-zinc system made possible by the inorganic/organic (I/O) separator (ref. 3), is summarized in figure 4. It should be noted here that operating procedures can influence the operational life exemplified by the increased life for discharged versus float stand in a real-time SYNC orbit test. Single-cell protection is also beneficial and now is ready for application.

One of the most important new batteries for space application is nickel-hydrogen, being developed primarily by Comsat (for SYNC) and the Air Force (for SYNC and LEO). Figure 5 provides a summary. It tolerates deep discharge and has intrinsically long-cycle-life capability. Electrolyte management in LEO has been a difficult problem, now apparently under control, but test data are very limited and the full energy-density potential has not been demonstrated. Recent reports (refs. 1,4) provide details of the technology.

Another metal-hydrogen system tolerant to deep discharge, namely silver-hydrogen, looks promising for long-life SYNC application. Figure 6 provides a summary. Its success is dependent upon the NASA I/O separator. Wet stand tests are just beginning, but based upon studies of the silver electrodes in many sealed silver-zinc cells, only about 3 percent loss of capacity should be expected per year in silver-hydrogen. It should be noted that in silver-hydrogen, the silver electrode remains intact and stable, quite different from silver-zinc. To obtain the energy-density goals it has been necessary to increase the utilization of the silver electrode to 75 percent. This has been achieved. The European Space Agency has a prime interest in this system.

The promises of substantially increased energy-density systems in the >100-watt-hour-per-pound range have motivated much research and development over the past 20 years. Based on alkali-metal negatives, these systems are currently receiving major attention by the Department of Energy (DOE) and the Electric Power Research Institute (EPRI) for electric vehicle and load-leveling applications, particularly the high-temperature lithium-iron sulfide and sodium-sulfur systems. The potential application of these systems to space has been discussed (refs. 1,5). More recent data (refs. 6,7,8) are summarized in figure 7. Generally, little experience is available in multicell batteries with these systems in the United States, though European groups seem to be advanced. The cycle life and demonstrated cell energy density are well below the technical goals at present. With the level of effort these systems are receiving, the technology should have an adequate chance to prove itself over the next few years if it is ever going to do so. If it does, space applications may benefit.

The ambient to 150° C systems depend upon either solid lithium or liquid

sodium contained in the sodium-ion-conducting ceramic, beta alumina. The former negative electrode does not seem to hold much promise for long cycle life needed for space, the latter does. Positives considered for combination with these negatives are shown in figure 7. The most exciting prospects appear to lie with the layered compounds that intercalate large concentrations of alkali-metal ion with no structural change. Investigations are well along based on lithium; work is just beginning with the sodium system (ref. 9).

In conclusion, nickel-cadmium improvements will maintain its preeminent position. Metal-hydrogen cells are here for SYNC orbit evaluation. Higher energy systems still are in their infancy but some may emerge within 3-5 years. Battery component technology and exploratory work must continue in order to meet the increasing demands of orbital electrical storage requirements.

FUEL CELLS FOR SPACE

The technology objectives for space fuel cells are long life, high specific power, reliability, maintainability and low cost. Technology programs lead to advances through cell components, materials and catalysts, thermal management, designs, controls and ancillaries. New approaches and systems concepts can make important contributions. Figure 8 summarizes the major NASA fuel cell applications, starting with Apollo to the Shuttle Orbiter and looking to the future. Two technologies, the solid polymer electrolyte (SPE) acid system and the matrix aqueous alkaline system, based on hydrogen and oxygen reactants, are available (ref. 10). Over the years since Apollo, the alkaline technology has experienced order-of-magnitude improvement in specific power, cost and system endurance. Figure 9 compares cell weights. The so-called lightweight technology represents the next step beyond the Orbiter and is based on the compact lightweight constructional approach shown in figure 10 (ref. 11). It is fair to characterize the alkaline system as having high performance with limited life and the SPE acid system as having modest performance with long life. Technology efforts have focused on the deficiencies and today the two technologies are converging (ref. 12). This is illustrated by the two plots in figure 11. The current space fuel cell efforts are summarized in figure 12.

For completeness, because of the very large technology and engineering development and demonstration efforts of DOE, EPRI, and the Gas Research Institute (GRI), the emerging fuel cell technologies (ref. 13) for commercial application in the time frames indicated are shown in figure 13 with a few pertinent comments regarding their space applicability. There seems to be little benefit associated with using phosphoric acid systems in space, aside from a potential cost advantage but at a performance penalty relative to the space fuel cells. The high efficiencies and high reject temperatures of molten carbonate and solid oxide systems may offer future benefits for space when the technologies mature.

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ORBIT	REQUIREMENT	CURRENT PERFORMANCE
LOW EARTH (LEO)	~6000 CYCLES/YEAR ~35 MIN. DISCHARGE ~55 MIN. CHARGE	Ni-Cd, 2-4 WHR/LB. < 30,000 CYCLES < 5 YEARS
SYNCHRONOUS (SYNC)	~84 CYCLES/YR (2 ECLIPSES) WET STAND MAX. 1.2 HR. DISCHARGE ~6.8 HR. CHARGE	Ni-Cd, 5 WHR/LB. ~ 300 CYCLES 3.5 YEARS

Figure 1. - Current orbital storage batteries.

NICKEL-CADMIUM

GOALS	APPROACH/STATUS
13 WHR/LB, 30,000 CYCLES 5 YRS (LEO) 13 WHR/LB, 900 CYCLES 10 YRS (SYNC)	o LIGHTWEIGHT COMPONENTS: CASE-HEADERS, NON-SINTERED AND POROUS PLASTIC PLATED PLAQUE, ELECTROCHEMICALLY IMPREGNATED PLAQUE, OPTIMIZE PRECHARGE AND REDUCE XS NEGATIVE MASS o NEW SEPARATORS: INORGANIC/ORGANIC (NEW TYPE), PBI, AMERACE o DEEP DISCHARGE RECONDITION: HIGH RATE RECOMBINATION OF H_2? o PROTOTYPE CELL DEMO BY 9/81 o MUCH PROGRESS MADE IN REDUCING WEIGHT FOR APPLICATIONS, E.G. NATO III
MULTIKILOWATT, >100 AH, LOW COST MAINTAINABLE (LEO)	o NEW TOROIDAL CONSTRUCTION FOR HEAT MANAGEMENT, REDUCED PARTS, SIMPLE ASSEMBLY o FEASIBILITY STUDY BEGINNING WITH FABRICATION OF MODEL CELL

Figure 2. - Secondary-battery technology - nickel cadmium.

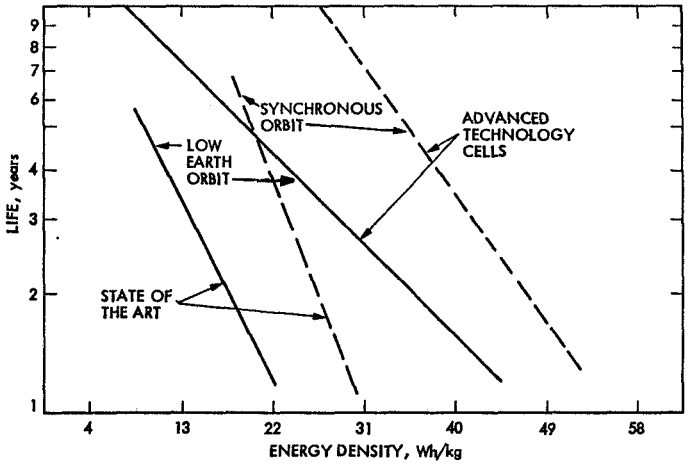


Figure 3. - Life as a function of energy density (assumes optimum temperature of 0^0 to 10^0 C).

SILVER-ZINC

GOAL	APPROACH/STATUS
24 WHR/LB, 450 CYCLES 5 YRS (SYNC)	o SEALED 40 AH; 12 AH CELLS DEVELOPED o INORGANIC/ORGANIC SEPARATOR (I/O) o 24 WHR/LB ACHIEVED IN PRODUCTION CELLS o REAL TIME SYNC TESTS: 60% DOD MAXIMUM 5 ECLIPSES (2.5 YRS) 210 CYC. FLOAT STAND 9 ECLIPSES (4.5 YRS) 380 CYC. DISCHARGED STAND o 40% DOD 1 CYCLE/DAY 1.2 HR DISCHARGE 450 CYCLES o SINGLE CELL PROTECTOR TECHNOLOGY DEVELOPED/TESTED ON 28V, 40 AH BATTERY: 60% IMPROVEMENT IN BATTERY LIFE OVER BATTERY LEVEL CONTROL; GENERALLY APPLICABLE AND AVAILABLE.

Figure 4. - Secondary-battery technology - silver-zinc.

NICKEL-HYDROGEN

GOALS	APPROACH/STATUS
22-25 WHR/LB, 900 CYCLES 10 YRS (SYNC)	o "PINEAPPLE SLICE" STACK CONSTRUCTION o NYLON, POLYPROPYLENE AND INORGANIC SEPARATORS USED
6000 CYCLES, 1 YR AND 30,000 CYCLES, 5 YRS (LEO)	o IMPROVED THERMAL, OXYGEN AND ELECTROLYTE MANAGEMENT NEEDED IN LEO o VOLUME ~1.5 - 2 X NI-CD o TEST DATA LIMITED, ~15 WHR/LB >650 CYCLES ACHIEVED IN LAB SYNC TEST o TECHNOLOGY AVAILABLE FOR EVALUATION o FLIGHT TEST OF NON-OPTIMIZED PROTOTYPE ON NTS-2 (8 WHR/LB) - RESULTS GOOD TO DATE, GOOD TEST FOR SYNC o AF FLIGHT TEST FOR LEO, PIGGY BACK EXPT. o COULD HAVE COMMERCIAL APPLICATION THUS REDUCED COST

Figure 5. - Secondary-battery technology - nickel-hydrogen.

SILVER-HYDROGEN

GOALS	APPROACH/STATUS
30 WHR/LB, 900 CYCLES >10 YRS (SYNC)	o STACK CONSTRUCTION - SLICES OR ROLLED, NOVEL USE OF HEAT PIPE CONSIDERED o I/O SEPARATOR, OTHERS UNSUITABLE
1 YR, HIGH RATE (LEO)	o STRESS ELECTROLYTE MANAGEMENT TECHNIQUES - ELECTROLYTE RESERVOIR PRINCIPLES o ~75% UTILIZATION AG ELECTRODE ACHIEVED o 20 AH, 30 WHR/LB CELLS >900 CYCLES @ 75% DEPTH 1.2 HR DISCHARGE, WET STAND TESTS BEGUN o SILVER ELECTRODE REMAINS STABLE INTACT; (DIFFERENT THAN AG-ZN), NO H_2 ELECTRODE POISONING o 50 AH >35 WHR/LB AEROSPACE WEIGHT CELLS READY 1979; USER EVALUATION NEEDED

Figure 6. - Secondary-battery technology - silver-hydrogen.

HIGH ENERGY DENSITY SYSTEMS >100 WHR/LB

- o ALKALI METAL NEGATIVES (Li, Na)
- o AEROSPACE/DOD GOALS PUSHED EARLY TECHNOLOGY WORK BEGINNING IN LATE 50s ⟶
- o ERDA/DOE - EPRI PROGRAMS NOW VERY LARGE FOR COMMERCIAL ELECTRIC VEHICLE AND LOAD-LEVELING APPLICATIONS ($ ~10M/YR)

A. HIGH TEMPERATURE (350°-450° C)

POSSIBLE BENEFIT FOR SPACE: EVENTUAL COST $40/kWHR, REJECT TEMP., HIGHER ENERGY DENSITY

1. LITHIUM $\left(\frac{Al}{Si}\right)$ - IRON SULFIDE

GOAL: 85 WHR/LB, >1000 CYCLES ~10 YR

STATUS:
- o 50 AH CELLS <35 WHR/LB >500 CYCLES, 4 HR RATE
- o 2 CELL BATTERY <20 WHR/LB ~600 CYCLES
- o LAB CELLS >1000 CYCLES; 60 WHR/LB, 33 CYCLES
- o LARGE BATTERY TEST IN VEHICLE LATE 1978

2. SODIUM-SULFUR WITH SOLID ELECTROLYTE

GOAL: 100-120 WHR/LB, 2500 CYCLES (>10 YR) - HIGH ENERGY CELL BETA-ALUMINA TYPE

STATUS:
75 AH CELLS: 55 WHR/LB; 170 CYCLES
MFG 1. ⊕ ELECTRODE, CONTAINER PROBLEMS
MFG 2. ⊕ PROBLEM SOLVED; 300 CYCLES CHROME-ALLOY MILD STEEL CONTAINER
FOREIGN TECHNOLOGY MORE ADVANCED

GLASS CAPILLARY FIBER TYPE

6AH CELLS: 60 WHR/LB; 217 CYCLES
GOOD TUBESHEET - FIBER INTERFACE
MANUFACTURABILITY GOOD
~$25/kWHR
SMALL CELLS 3800 CYCLES

B. ORGANIC ELECTROLYTE (AMBIENT TO 150° C)

- o LITHIUM (SOLID) OR SODIUM (LIQUID)/SOLID ELECTROLYTE (>100° C) FOR NEGATIVE ELECTRODES
  - LITHIUM RECHARGEABILITY LIMITED TO ~100 CYCLES AT PRESENT; SOME REPORTS OF BREAKTHROUGH TO 1000s OF CYCLES
  - SODIUM (LIQ)//BETA ALUMINA - MANY THOUSANDS OF DEEP CYCLES DEMONSTRATED
- o FOR POSITIVE ELECTRODES
  DISSOLVED SULFUR OR SOLID INSOLUBLE TRANSITION METAL DICHALCOGENIDE OPERATING IN ORGANIC ELECTROLYTES ARE MOST PROMISING CONCEPTS FOR GOOD RATES AND LIFE
  - o STABILITY OF CONCENTRATED ALKALI POLYSULFIDES IN ORGANICS APPEAR LIMITED FOR LONG LIFE APPLICATIONS
  - o TRANSITION METAL DICHALCOGENIDES HAVE LAYERED STRUCTURES ACCEPTING LARGE CONCENTRATION OF ALKALI IONS WITHOUT STRUCTURAL CHANGE IN WHICH ALKALI IONS DIFFUSE RAPIDLY. EXCITING OPPORTUNITIES; A FEW EXAMPLES.

$Li \,/\, \text{VARIOUS ELECTROLYTES} \,/\, Li_xTiS_2$ <100 $\frac{WHR}{LB}$ >250 CYCLES 10 MA/CM^2

- o MAJOR DEVELOPMENT EFFORT IN PROGRESS

$Li \,/\, \text{ELECTROLYTE} \,/\, Li_xCr_yV_zS_2$ ≈115 $\frac{WHR}{LB}$ RATE?

$Na_L \,/\, \text{BETA ALUMINA} \,/\, \text{ORGANIC ELECTROLYTE} \,/\, Na_xNi\,PS_3$ ≈ 125 $\frac{WHR}{LB}$ PRACTICAL ESTIMATE

- o EXPLORATORY WORK BEGINNING

Figure 7. - Secondary-battery technology - high-energy-density systems.

PAST:

BIOSATELLITE (SPE)
GEMINI (SPE)
APOLLO (1.5 KW, 1962, ALKALINE)

PRESENT:

SHUTTLE ORBITER (12 KW, 1973, ALKALINE)

FUTURE:

ORBITAL TRANSFER VEHICLE (OTV)
SPACE BASE - SOLAR PHOTOVOLTAIC ENERGY STORAGE
(WITH ELECTROLYZER)
SHUTTLE DERIVATIVES

Figure 8. - Major NASA fuel cell applications.

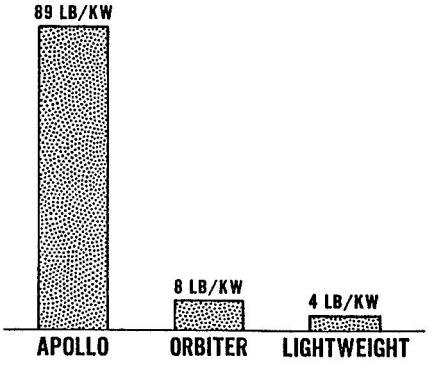


Figure 9. - Cell weight comparison.

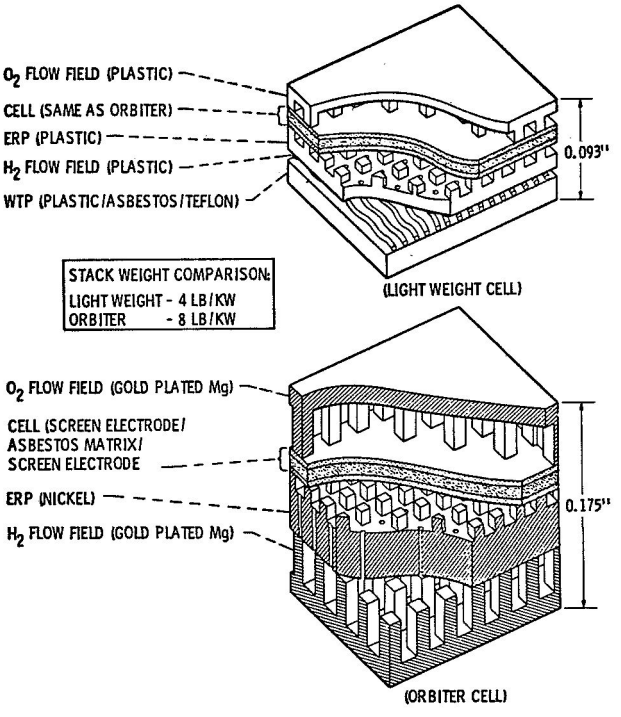
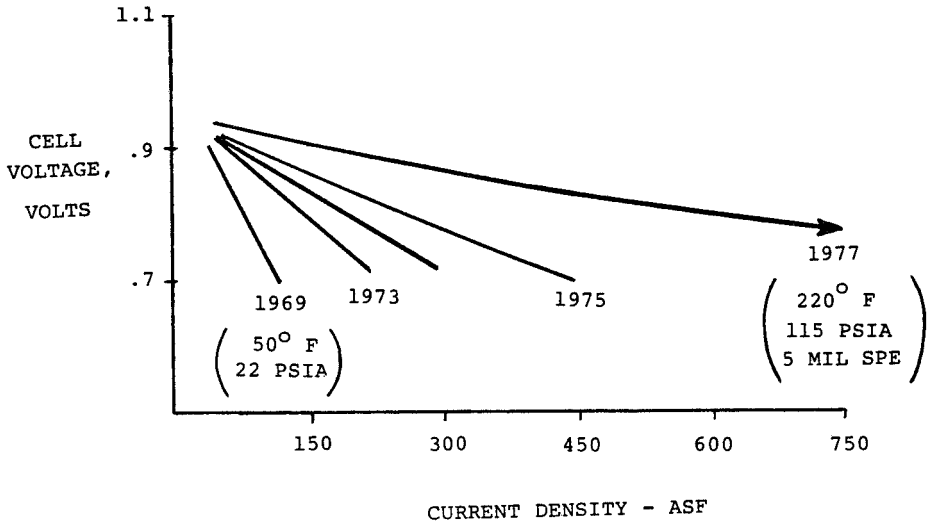
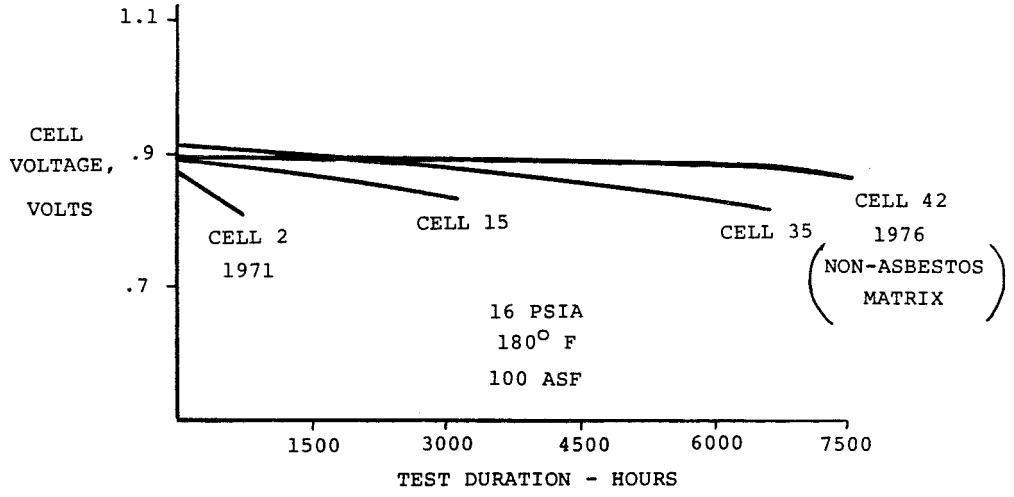


Figure 10. - Structural comparison: lightweight fuel cell versus orbiter fuel cell.



(a) Acid SPE fuel cells.



(b) Lightweight alkaline fuel cells.

Figure 11. - Improvements in performance of acid SPE and lightweight alkaline fuel cells.

ALKALINE - H_2/O_2

- o 20 LB/KW, 10,000 HR @ 200 ASF, 185° F USING PROPELLANT GRADE REACTANTS DEMONSTRATED AT CELL LEVEL
  - POWER PLANT DEVELOPMENT BEGUN
- o 20 LB/KW, >40,000 HR, 0.91V @ 200 ASF, 180° F CELL DEVELOPMENT BEGUN
  - LIGHTWEIGHT OXIDATION-RESISTANT MATERIALS DEFINED
  - NEW ELECTROCATALYSTS INCL. SUPPORTED COMMERCIAL TYPE
  - NEW PBI MATRIX
- o 6 LB/KW, >3000 HR, 0.9V @ 1000 ASF, 250-300° F USING PROPELLANT GRADE REACTANTS
  - AS ABOVE, SAME MATERIALS REQUIREMENTS
  - RESEARCH CELL ACHIEVED >0.90V @ 1000 ASF FOR 16 HRS
  - HIGH CURRENT DENSITY REDUCES COST

ACID (SPE) - H_2/O_2

- o 15-20 LB/KW, >40,000 HR, 0.95 @ 120 ASF, 180° -220° F, BREADBOARD SYSTEM BEING BUILT FOR TESTING
  - HUMIDIFICATION OF REACTANTS IS KEY TO PERFORMANCE
  - ENDURANCED ACHIEVED IN CELLS

Figure 12. - Space fuel cell technology thrust.

COMMERCIAL SYSTEMS - LOW COST ~$300/KW (DOE-EPRI-GRI, ~$40M/YR AND GROWING)

PHOSPHORIC ACID (1980-1985)

- LIQUID SEALS A PROBLEM FOR SPACE
- INEFFICIENT RELATIVE TO ALK. OR SPE; 190° C
- ENDURANCE @ 300 ASF SUFFICIENT FOR 40,000 HR SYSTEM (PROVIDING ACID INVENTORY CAN BE MAINTAINED)

MOLTEN CARBONATE (1990)

- 650° C TO OPERATE; EFFICIENT
- CELL ENDURANCE DEMONSTRATED TO 13,000 HRS @ 100 ASF
- HIGH REJECT TEMP.
- MAINTAINING TEMP. IN SPACE?

SOLID OXIDE (2000)

- 1000° C OPERATE; EFFICIENT
- CELL ENDURANCE DEMONSTRATED TO ~40,000 HRS @ 120 ASF
- CELL INTERCONNECT PROBLEM SOLVED
- ALL SOLID STATE SYSTEM
- HIGH REJECT TEMP.
- MAINTAINING TEMP. IN SPACE?

Figure 13. - Possible future fuel cell technology opportunities in space.